Hubble Space Telescope Far Ultraviolet Spectroscopy of the Dwarf Nova VW Hyi in Superoutburst [1]

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ABSTRACT

We obtained three consecutive HST spectroscopic observations of a single superoutburst of the dwarf nova VW Hydri. The spectra cover the beginning, middle, and end of the superoutburst. All of the spectra are dominated by strong absorption lines due to CIII (1175 Å), Lyman alpha (1216 Å), NIV (1238 Å, 1242 Å), SII (1260-65 Å), SIII (1300 Å), CII (1335 Å), SIV (1394 Å, 1402 Å) and CIV (1548 Å, 1550 Å). We discuss the evolution of the far UV energy distribution and line structure during the superoutburst. We note the absence of any P Cygni line structure in the STIS spectra. Using state of the art accretion disk models by Wade and Hubeny, we have determined accretion rates for all three spectra, for two white dwarf masses, 0.55 $M_{\odot}$ and 0.8 $M-\odot$. For both white dwarf masses the accretion rate during superoutburst decreased by a factor of two from early to late in the superoutburst. The average accretion rate during superoutburst is $3 - 6 \times 10^{-9} M_{\odot}/yr$ depending on the white dwarf mass.

Subject headings: accretion, accretion disks - novae, cataclysmic variables - stars: dwarf novae - stars: individual (VW Hydri) - white dwarfs

1. Introduction

Dwarf novae (DNe) are a subclass of cataclysmic variable (CV) systems, in which a white dwarf (WD, the primary) accretes hydrogen-rich matter from a low-mass main sequence-like star (the secondary) filling its Roche lobe. In these systems, the transferred gas forms an accretion disk around the WD. It is believed that the accretion disk is subject to a thermal-viscous instability that causes cyclic changes of the accretion rate. A low rate of accretion ($\approx 10^{-11} M_{\odot}$ yr^{-1}) quiescent stage is followed every few weeks to months by a high rate of accretion ($\approx 10^{-8} M_{\odot}$ yr^{-1}) outburst stage of days to weeks. These outbursts (dwarf nova - DN accretion event or nova-like high state), are believed to be punctuated every few thousand years or more by a thermonuclear runaway (TNR) explosion: the classical nova (Hack & la Dous 1993).

VW Hyi is a key system for understanding DNe in general. It is one of the closest (Warner 1987, placed it at 65 pc), brightest and best-studied example of an SU UMa-type DN and it lies along a line of sight with an exceptionally low interstellar column (Polidan, Mauche & Wade 1990, estimated the HI column to be $\approx 6 \times 10^{17}$ cm^{-2}), which has permitted study of VW Hyi in nearly all wavelength ranges, including detection in the usually opaque extreme ultraviolet [EUVE (Mauche 1996)]. Coherent and quasi-coherent soft X-ray oscillations and a surprisingly low luminosity boundary layer (BL) have been detected (Belloni et al. 1991; Mauche et al. 1991). VW Hyi is below the CV period gap near its lower edge, with an orbital period of 107 minutes and a quiescent optical magnitude of 13.8. Below the period gap, gravitational wave emission is thought to drive mass transfer, resulting in very low accretion rates during dwarf nova quiescence.

Systems of the SU UMa class undergo both normal DN outbursts and superoutbursts. For VW Hyi, the normal outbursts last 1-3 days and occur every 20-30 days, with peak visual magnitude of 9.5. The superoutbursts last 10-15 days and occur every 5-6 months, with peak visual magnitude reaching 8.5. The mass of the accreting WD was estimated to be 0.63 $M_{\odot}$ (**?**), but more recently a gravitational redshift determination yielded a larger mass $M_{wd} = 0.86 M_{\odot}$ (Sion et al. 1997). The inclination of the system is $\approx$ 60 degrees (Huang et al. 1996a,b).

While the physical properties of the accreting white dwarf in VW Hyi and its response to heating by the outbursts and superoutbursts have been derived from HST spectra obtained during quiescence, relatively little has appeared on the accretion rate of VW Hyi during

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outbursts and superoutbursts. In particular, the FUV spectra in outburst or superoutburst have not as yet been compared with realistic accretion disk models with vertical structure. Note however that previous models used by Huang et al. (1996a) were stellar atmosphere proxies to a proper disk which nonetheless provided an excellent approximation to vertical structure models since the disk is optically thick, and it has been shown in the literature that for optically thick disks there is little difference between stellar atmospheres and disk-proper models.

We have obtained a series of HST spectra of VW Hyi during a superoutburst. In Section 2, we describe the observations and provide a description of the spectra that were obtained. In Section 3, we compare the spectrum to models in an attempt to account for the continuum energy distribution and the line spectrum. In Section 4, we discuss the results of our synthetic spectral analysis and in Section 5, we briefly summarize our conclusions.

2. Observations

The observations of VW Hydri were obtained between 20 May 2000 and 25 May 2000, during the decline from superoutburst. For all three observations, the instrumental setup used STIS with the FUV-MAMA detectors in ACCUM mode. The spectra had a center wavelength of 1425A and a bandwidth of 595A, for a total wavelength range of 1140.0A to 1735A. Specific details of the exposures are given in table 1. There were no apparent problems with any of the spectra.

The most obvious absorption lines are NII (1085.7 Å), CIII (1174.9-1176.4 Å), Lyman Alpha (1216 Å), N V (1238, 1242 Å), Si II 1260-1265 Å), Si III + O I (1300 Å), C II (1335 Å), O V (1371 Å), Si IV (1393, 1402 Å) and C IV (1548, 1550 Å). None of the absorption features exhibit P Cygni structure or obvious asymmetries which are typical signatures signatures of wind outflow. The absorption lines gradually weaken from the first to the third spectrum as the continuum in the relatively line free region at 1460 Ådeclined from 1.3×10^{-11} ergs/cm^2/s/Å(early) to 6×10^{-12} ergs/cm^2/s/Å(late). This is accompanied by a decrease in the slope of the continuum from early to late in the superoutburst.

3. Analysis

In this section we describe the procedure we followed to assess the contribution of the accretion disk, and derive the accretion rate onto the white dwarf during the superoutburst. This procedure consists of comparing the observed HST STIS spectra of VW Hyi with a grid of theoretical accretion disk spectra for adopted system parameters and varying accretion disk parameters. The best fit models are then obtained using a χ^2 minimization fitting procedure. Details of the codes and the χ^2_ν (χ^2 per degree of freedom) minimization fitting procedures are discussed in detail in Sion et al. (1995) and Huang et al. (1996a), and will not be repeated here.

For the accretion disk spectrum, we used the grid of accretion disk spectra computed by Wade & Hubeny (1998), who use a slightly different version of the code TLUSTY Hubeny (1988) named TLUSDISK to generate the theoretical spectrum of an accretion disk. The optically thick accretion disk model is made of a collection of rings. The disk models are computed assuming LTE and vertical hydrostatic equilibrium. The radial temperature structure in the disk is governed by the assumption of steady state accretion equilibrium where each annulus receives the same amount of mass as it loses (i.e. the disk gains as much mass from the Roche lobe filling donor star as the white dwarf accretes from the disk). Irradiation from external sources is neglected. Local spectra of disk annuli are computed taking into account line transitions from elements 1-28 (H through Ni). Limb darkening as well as Doppler broadening and blending of lines are taken into account.

Before we carried out the model fits, we masked wavelength regions where strong resonance line absorption due to zero volt resonance doublets appear in the HST spectra. The regions we masked in the fitting are N V [1228-1250Å] and C IV [1530-1552Å] as well as any negative fluxes. For the accretion disk fits, we "fine-tuned" the derived accretion rate of the best-fitting disk model by changing the accretion rate in increments of 0.1 over the range 0.1 to 10, on the assumption that the disk fluxes scale linearly over that range.

3.1. The Accretion Disk Models

In superoutburst, a reasonable expectation is that the far UV radiation should be dominated by the light of the luminous accretion disk. Moreover, since it is expected that at least during part of the superoutburst, the accretion disk should closely approximate a steady state, we explored whether an accretion disk model would produce better agreement with the *HST STIS* spectra. Although one expects the inner region of the accretion disk in VW Hyi to be optically thin during quiescence, This is not the case during outburst or superoutburst and led us assess how well optically thick steady state disks can represent the observations.

In the present work we used the grid of accretion disk spectra of Wade & Hubeny (1998) consisting of 26 different combinations of M_{wd} (0.35, 0.55, 0.80, 1.03 and 1.21 $M_\odot$) and $\dot{M}$ ($log\dot{M} =$ -8.0, -8.5, -9.0, -9.5, -10.0 and -10.5 $\dot{M}$ yr^{-1}; see Table 2 in Wade & Hubeny

(1998)). The spectra are presented for six different disk inclinations i (8.1, 18.2, 41.4, 60.0, 75.5 and 81.4 degrees). The models fluxes include the effects of limb darkening, the projection of fluxes as a function of the inclination angle, and are scaled to a distance of 100 pc where the distance is related to the scale factor as

$$d = 100(pc)/\sqrt{S}.$$

For a system as well-studied as VW Hyi, we adopted widely used parameters in the literature. We fixed the distance d = 65 pc, fixed the orbital inclination at $i = 60$ degrees but assumed two values of the white dwarf mass, M_{wd}. The synthetic disk spectra were then fitted to the three superoutburst spectra by our χ^2 minimization routine. The best-fitting accretion disk models are listed in Table 2 corresponding to $M_{wd} = 0.55M_{\odot}$ and $M_{wd} = 0.8M_{\odot}$. We list in column (1) the part of the superoutburst in which the spectrum was taken; (2) the white dwarf mass adopted; (3) the adopted orbital inclination; (4) log of the accretion rate in solar masses per year resulting from the best-fitting disk model; (5) the χ^2 value corresponding to the best fit; (6) the value of the increment which produced the best refined disk model fit (see section 3).

The best-fitting accretion disk models to the three HST spectra for both values of the white dwarf mass are displayed in Figure 1 for the early spectrum, Figure 2 for the middle spectrum and Figure 3 for the late spectrum. All three spectra are well-fit by steady state accretion disk models except for the observed continuum shortward of Lyman Alpha where the theoretical disk flux overpredicts the observed flux. We discuss the results of these fits in the following section.

4. Summary and Conclusions

The high quality HST STIS together with the currently accepted orbital inclination and reasonable distance (65 pc) for VW Hydri enabled a determination of the accretion rate during a superoutburst as a function of time within the superoutburst. For assumed white dwarf masses $M_{wd} = 0.6M_{\odot}$ and $M_{wd} = 0.8M_{\odot}$, the derived average accretion rates during superoutburst are, respectively $6(\pm-1)\times10^{-9}$ $M_{\odot}$/yr and $3(\pm-1)\times10^{-9}$ $M_{\odot}$/yr. All of the best-fitting models show a flux excess relative to the observations. This flux deficit relative to the models, shortward of Lyman α, may be due to the possibility that the accretion disk in VW Hydri is modestly truncated hence having a cooler inner disk region than the untruncated accretion disk model. The accretion rate late in the superoutburst as declined by a factor of two relative to the accretion rate early in the superoutburst.

Huang et al. (1996a) modeled an HST FOS G130H spectrum of VW Hyi taken roughly five days after the optical rise to superoutburst in October, 1993. This was approximately the same time that elapsed before the first STIS E140M spectrum was taken during the May, 2000 superoutburst reported in this paper. For a white dwarf mass of $M_{wd} = 0.6 M_{\odot}$ and a distance of 90 pc, Huang et al. (1996a) found a best-fitting disk model of $3(\pm - 1) \times 10^{-9}$ $M_{\odot}$/yr while in the present paper, with d = 65 pc, accretion rates of $8(\pm - 1) \times 10^{-9}$ $M_{\odot}$/yr and $4(\pm - 1) \times 10^{-9}$ $M_{\odot}$/yr were determined for white dwarf masses $M_{wd} = 0.6 M_{\odot}$ and $M_{wd} = 0.8 M_{\odot}$, respectively. The same sharp cores of N V and C IV detected by Huang et al. (1996a) are seen at N V in Figures 1,2, and 3 but not C IV in this paper. In Huang et al., the sharp cores at C IV reveal a hint of inverse P Cygni structure as though either infall onto the white dwarf or superposition of an inhomogeneous accretion stream is being seen. The C IV profile in the STIS E140M spectra reported in this paper do not reveal the resolved sharp doublet cores in C IV but rather a merged sharp core.

Given our derived accretion rates, it may be possible to carry out quasi-static evolutionary model simulations at these rates, to compare with the amount of white dwarf cooling evident from model analyses of post-outburst and post-superoutburst far ultraviolet spectra. We leave this for a future exploration.

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Table 1. HST STIS Observations of a Superoutburst of VW Hydri

Dataset	Exposure Start Time	Exposure Time	Aperture	Disperser	SOB Phase
O5E202010	2000-05-20 14:06:00	2512.8	0.2×0.2	E140M	Early
O5E203010	2000-05-22 17:30:00	2512.8	0.2×0.2	E140M	Middle
O5E204010	2000-05-25 14:34:00	2512.8	0.2×0.2	E140M	Late

Table 2. Accretion Disk Model Fitting Results

SOB Phase	WD($M_\odot$)	i	log $\dot{M}$	χ^2	$f \times \dot{M}$
Early	0.55	60	$-8.097(8 \times 10^{-9})$	2.905	0.8
	0.8	60	$-8.386(4 \times 10^{-9})$	2.288	1.3
Middle	0.55	60	$-8.222(6 \times 10^{-9})$	2.581	0.6
	0.8	60	$-8.500(3 \times 10^{-9})$	2.605	1.0
Late	0.55	60	$-8.459(3.5 \times 10^{-9})$	2.950	1.1
	0.8	60	$-8.745(1.8 \times 10^{-9})$	3.036	1.8

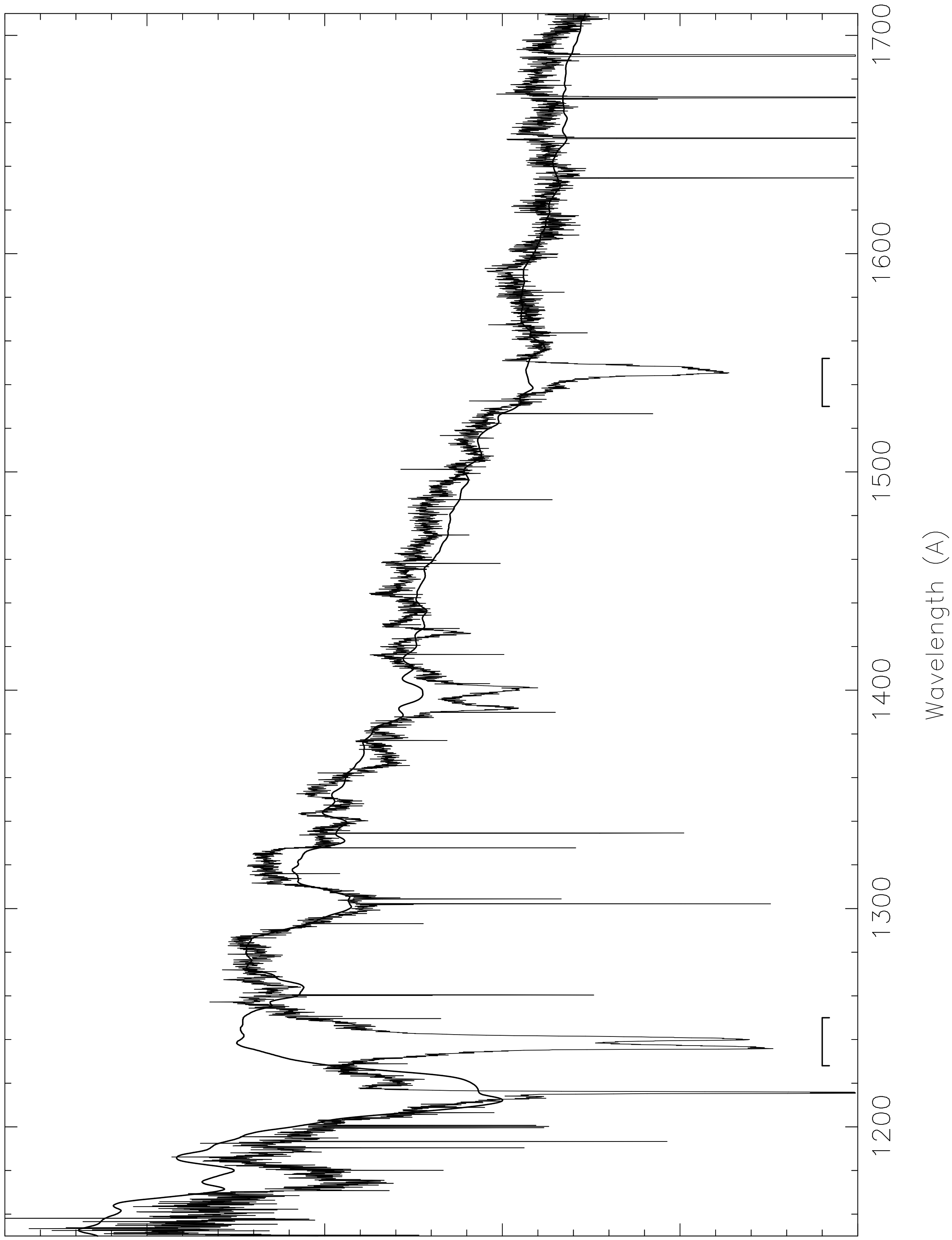


Fig. 1.— Fig.1 - The earliest of the three spectra was taken on 20 May 2000, near the peak

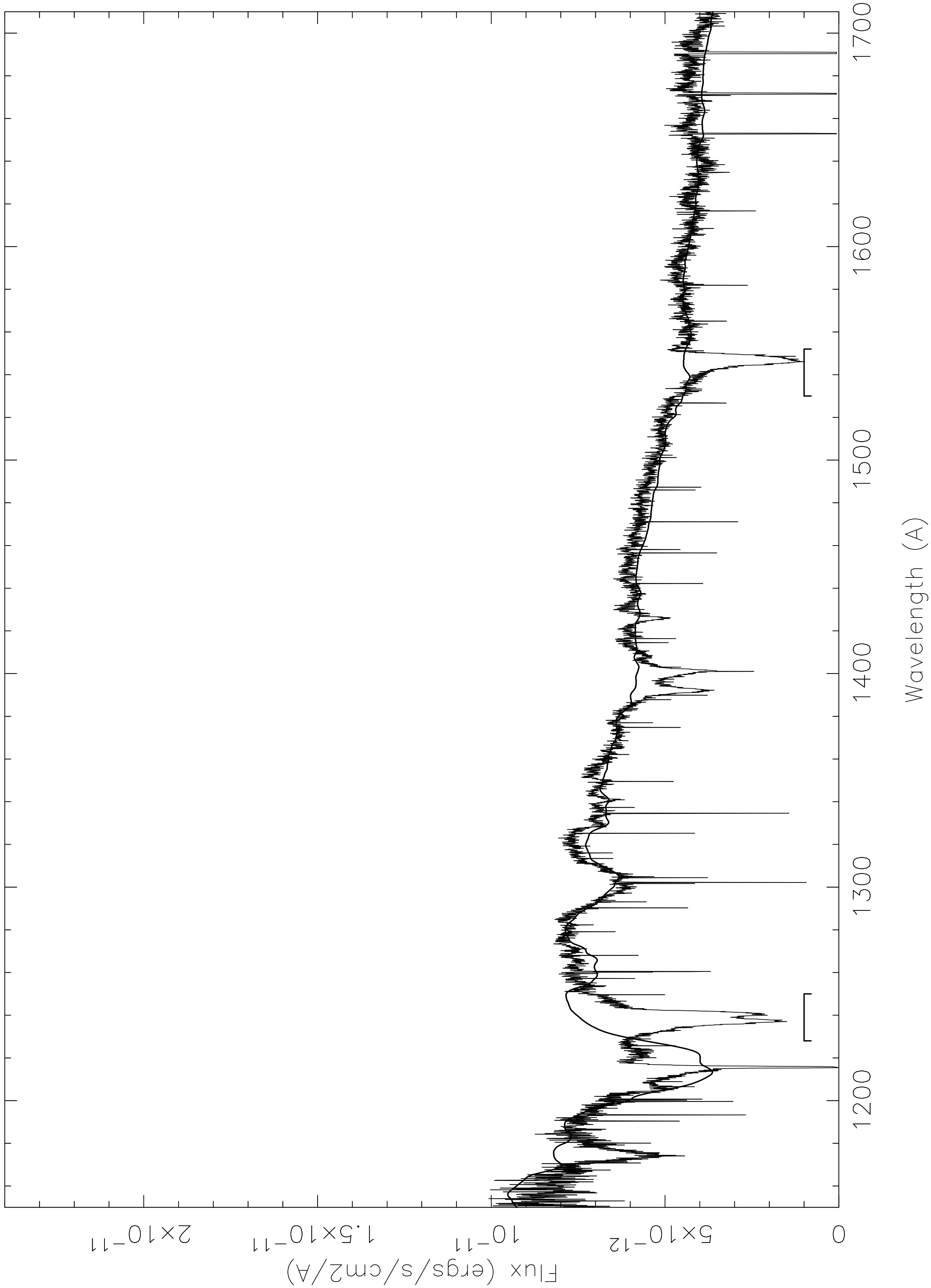


Fig. 2.— Fig.2 - The second spectrum was taken on 22 May 2000, as the flux was declining

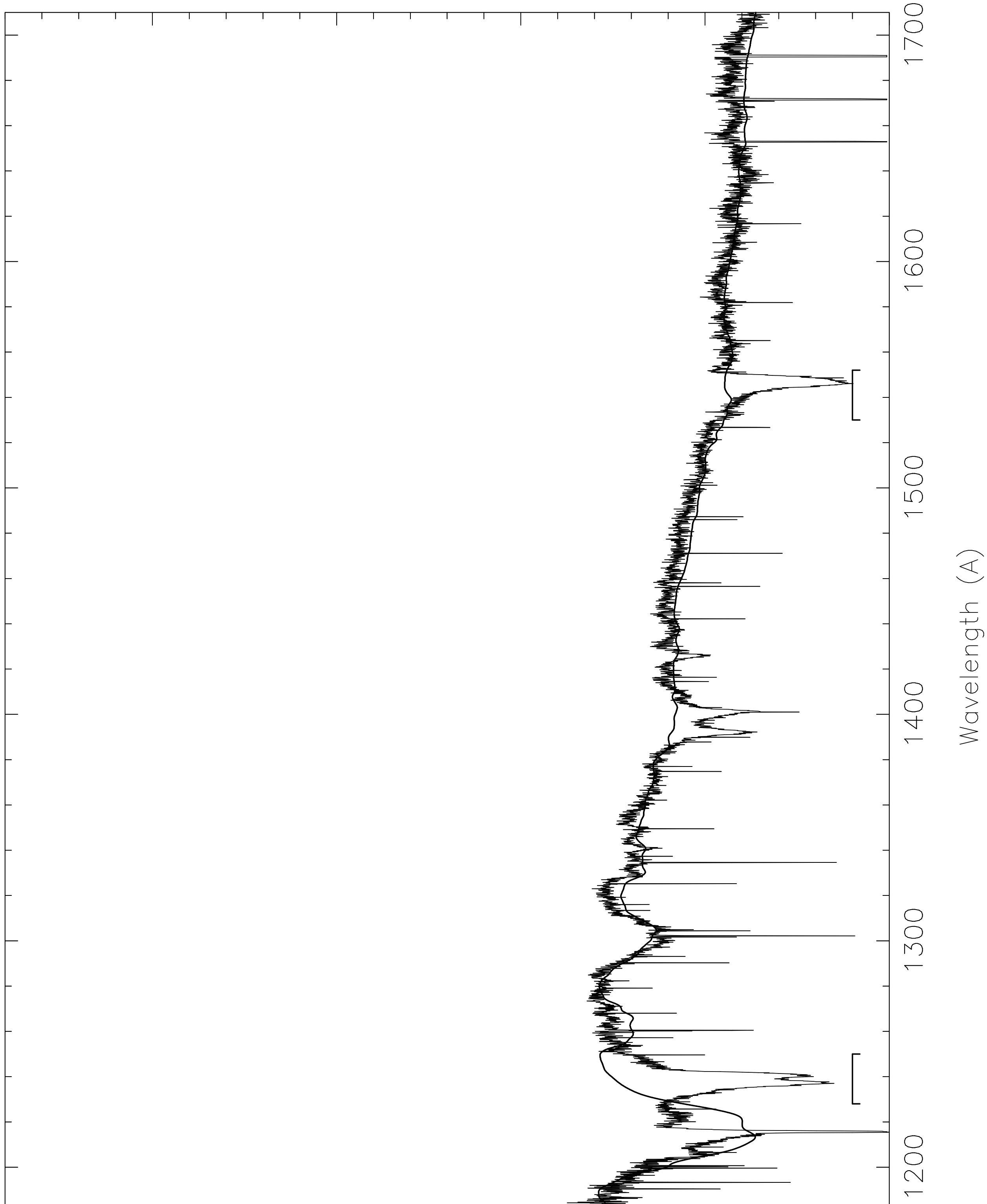
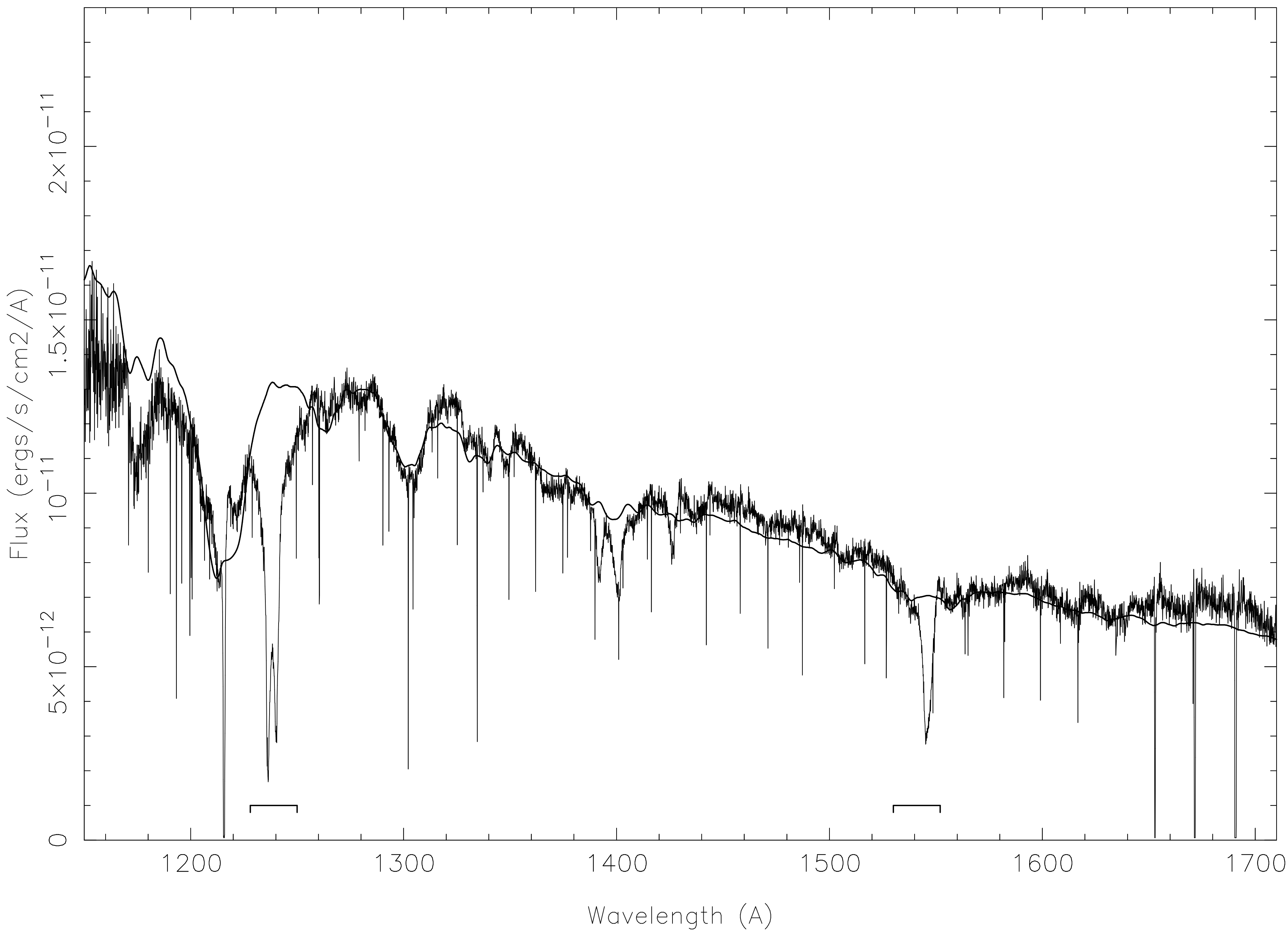


Fig. 3.— Fig.3 - The third and final spectrum was taken on 25 May 2000, near the end of the


Flux (ergs/s/cm2/A)
0
5×10⁻¹²
10⁻¹¹
1.5×10⁻¹¹
2×10⁻¹¹
1200
1300
1400
1500
1600
1700
Wavelength (A)